NSTX-U Transport & Turbulence (T&T) research

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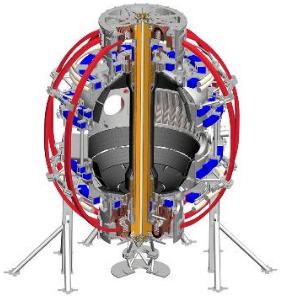

OUTLINE

- Background and research goals
- Recent highlights supporting research plans
- Near term and longer-term research plans
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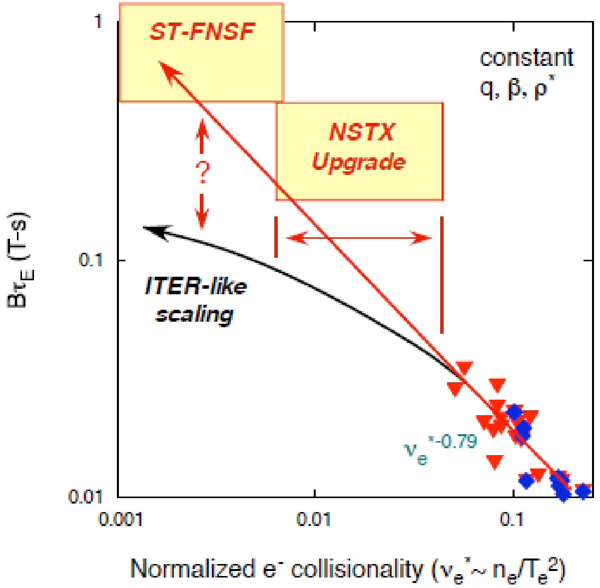
Understanding confinement scaling ($\tau_E \sim 1/\nu$) at low collisionality is critical for future spherical tokamaks (ST)

- In NSTX and MAST H-modes, dimensionless confinement time scales inversely with collisionality, $\Omega_{ci}\tau_E \sim \nu_*^{-0.8}$ [Kaye, NF (2007, 2013); Valovic, NF (2011)]

- Next generation STs (Pilot Plant, FNSF, CTF) will operate at lower ν_*



⇒**What determines transport & confinement scaling?**

- How does this influence access to operational scenario goals (e.g. 100% non-inductive)? [*see Battaglia talk*]

- Conventional (R/a~3) tokamak H-modes are thought to be governed by electrostatic toroidal drift waves:
  - ($k_\perp\rho_i$~1) Ion temperature gradient (**ITG**, $\gamma \sim \nabla T_i$) & trapped electron mode (**TEM**, $\gamma \sim \nabla T_e, \nabla n_e$)
  - ($k_\perp\rho_e$~1) Electron temperature gradient (**ETG**, $\gamma \sim \nabla T_e$)

Many features of low aspect ratio + high beta are stabilizing to electrostatic toroidal drift waves

Stabilizing effect		Impact
Short connection length	⇒	**Smaller average "bad curvature"**
Quasi-isodynamic (~constant B) at high β, strong Shafranov shift		**Grad-B drifts stabilizing** [Peng & Strickler, NF 1986]
Large fraction of trapped electrons, BUT precession weaker at low A		**Reduced TEM drive** [Rewoldt, PoP 1996]
Strong coupling to $\delta B_{\perp}$ at high β		**Stabilizing to ES-ITG** [Kim, Horton, Dong, PoFB 1993]
Small inertia (nmR^2) & uni-directional NBI heating gives strong toroidal flow & flow shear		**E×B shear stabilization ($dv_{\perp}/dr$)** [Biglari, Diamond, Terry PoFB 1990]

- **Stabilization of ITG consistent with observed neoclassical ion transport: $Q_i \approx Q_{i,NC}$ & $\Gamma_{imp} \approx \Gamma_{imp,NC}$**
- BUT high beta drives electromagnetic instabilities:
  - Microtearing modes (**MTM**) ~ $\beta_e \cdot \nabla T_e$
  - Kinetic ballooning modes (**KBM**) & energetic particle modes (**EPM**) ~ $\alpha_{MHD} \sim q^2 \nabla P/B^2$ & ∇P_{fast}
- Large shear in parallel velocity can also drive parallel velocity gradient (**PVG**) instability ~$dv_{||}/dr$

NSTX-U T&T research addresses high-priority ST-specific transport issues

T&T RESEARCH GOALS (thrusts from five-year plan):

- Extend confinement scaling to much lower collisionality at high beta & strong shaping
- Distinguish mechanism(s) underlying ST energy confinement scaling, as well as particle, impurity & momentum transport
- Validate first-principle and reduced models using a range of scenarios, e.g. from L-mode to 100% non-inductive H-mode

⇒ *Enable more reliable extrapolation & prediction to future ST-based devices*

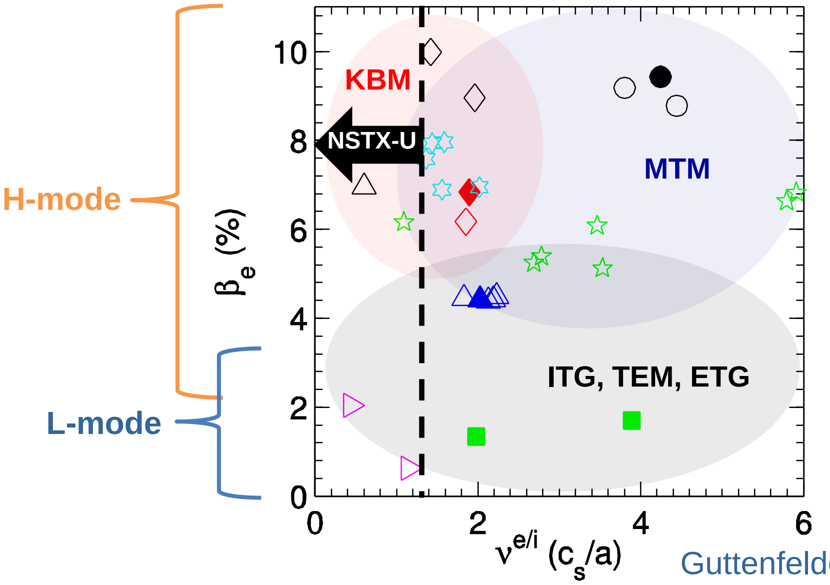
Leverage cutting-edge ST capabilities of NSTX-U:

- Highest field and heating power with strong shaping → access to highest β at lower ν_*
- Unique current, flow profile & fast-ion phase space control from 2nd off-axis NBI + 3D coils
- RF heating (HHFW) for flexible thermal & impurity transport studies (*see Perkins talk*)
- Comprehensive suite of turbulence diagnostics
  - Multi-scale density fluctuations (δn): BES (low-k), FIR high-k_θ scattering system, DBS (low- to intermediate-k)
  - Magnetic field fluctuations (δB): CPS

The challenges confronted by NSTX-U T&T research benefit the broader tokamak community & burning plasma regimes

- Unique in accessing wide range in (β, ν) → *requires validating a variety of theoretical drift wave transport mechanisms*
  - Predominantly in electron-loss dominated regimes (*burning plasma relevant*)

Local **GYRO NSTX analyses at r/a~2/3**



Guttenfelder, NF (2013)

The challenges confronted by NSTX-U T&T research benefit the broader tokamak community & burning plasma regimes

- Unique in accessing wide range in (β, ν) → *requires validating a variety of theoretical drift wave transport mechanisms*
  - Predominantly in electron-loss dominated regimes (*burning plasma relevant*)

- High beta, strong shaping & significant fast ion content challenges numerical codes → *requires improved EM simulations & reduced transport models*
  - Important for high performance AT scenarios & burning plasma regimes (*significant ITPA T&C activity*)

- Global & compressional Alfvén eigenmodes (GAE/CAE) influence thermal electron transport* → *requires validating stability thresholds & saturation mechanisms*
  - Important to understand dependence on $V_{fast}/V_{Alfvén}$, β_{fast}/β_{tot}, and fast-ion phase space and consequences in burning plasma regimes *(see Podestà talk)*

*Transport occurs through stochastic electron orbits & CAE-KAW coupling (backup slides)

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See Y. Ren, NF (2017) for recent review paper

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FY18 Milestone & collaborations address priority T&T issues in preparation for NSTX-U operations

- R(18-3) milestone: “Validate & develop electron thermal transport models in STs”
  - Model validation (TGLF, MMM, Rafiq-MTM)
  - Model qualification by comparing with first-principles gyrokinetics
  - Data analysis & uncertainty quantification

Collaboration with GA & Lehigh U.

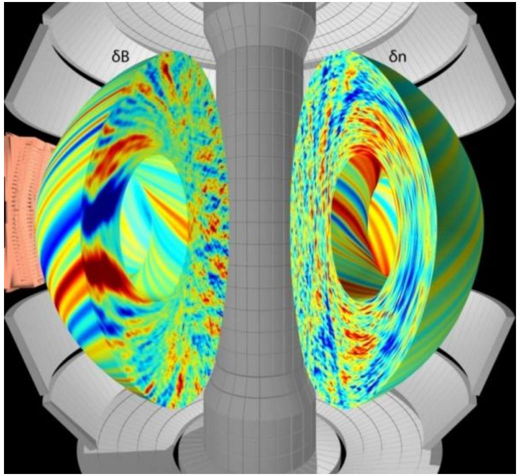
- Active DIII-D collaboration from 2017 “NSTX-U campaign” (*see Kaye talk*)
  1. “Investigate ν_* scaling at ST-relevant q95” → Clarify role of R/a & q95 on $\tau_E \sim \nu_*^{\alpha}$
  2. “Validate electromagnetic turbulence predictions” → Validate GK w/ CPS ($\sim\delta B$) + synth. diagnostic
  3. “CAE ω and k dependence on beam pitch angle and energy” → Measure onset, validate sims.

- MAST-U collaboration in FY18-20
  - Transport analysis & confinement scaling at increased B_T, I_P

High β NSTX transport validation studies highlight the importance of electromagnetic microturbulence

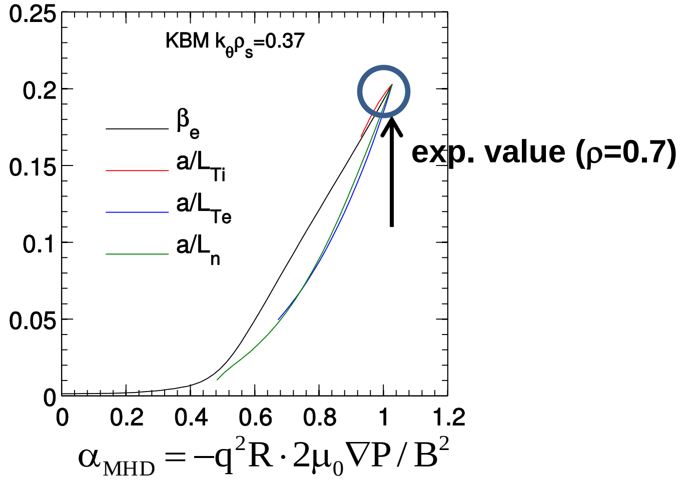
- Nonlinear simulations of core MTM turbulence predict significant transport at high β & ν; collisionality scaling ($\chi_{e,MTM}$~ν_e) consistent with global confinement (τ_E~1/ν)
- At high β & <u>lower ν</u>, KBM modes are predicted *in the core* ⇒ may set ultimate limit to confinement scaling -- *many similarities to DIII-D/EAST high-β_{pol}* (Staebler APS 2017, Guttenfelder APS 2015)

NSTX MTM simulation (<u>high-ν</u>)



Guttenfelder, PRL (2011), PoP (2012), NF (2013)

KBM linear growth rates (<u>low-ν</u>)



- **High priority goal of T&T research is to directly measure internal δB via cross polarization scattering (CPS) to validate simulations (collaboration with DIII-D & UCLA) [*see Kaye talk*]**

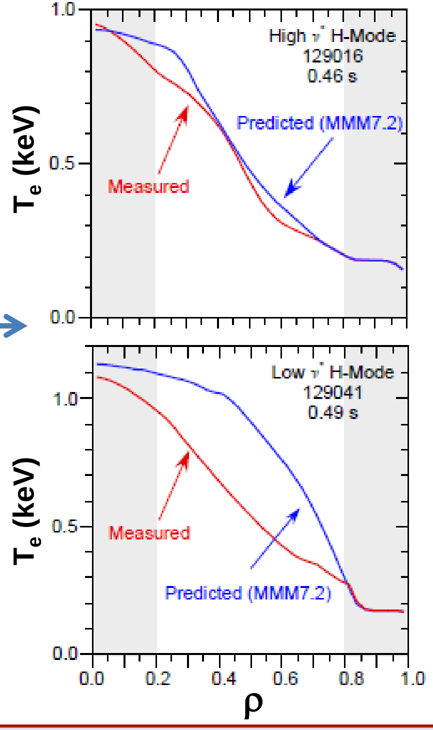
Nonlinear gyrokinetic simulations & transport models are evolving to address challenges at high β

- Global electrostatic simulations illustrate importance of non-local effects at finite-$\rho^*=\rho_i/a$ (Ren, NF 2013, IAEA 2016) (*backup slides*)
  - Global GTS simulations have also uncovered unique DTEM mechanism with $\chi_{e,DTEM}\sim\nu_*$ scaling (Wang, PoP 2015, NF 2015)
  - Development of global electromagnetic GK codes GTS, XGC1 is advancing (*PPPL theory*)

- Recently developed kinetic/fluid MTM model recovers many gyrokinetic trends (Rafiq, PoP 2016, APS 2016); profile predictions being tested →
  - T_e predictions using Rebut-Lallia-Watkins MTM model useful for high-ν_* discharges, but does not capture correct parametric scalings (Kaye, PoP 2014)
  - Updating TGLF by qualifying with gyrokinetics over broader range of ST scenarios, β & R/a (R18-3 Milestone)

⇒ **Is there an optimal aspect ratio for core performance goals? (*see Menard talk*)**

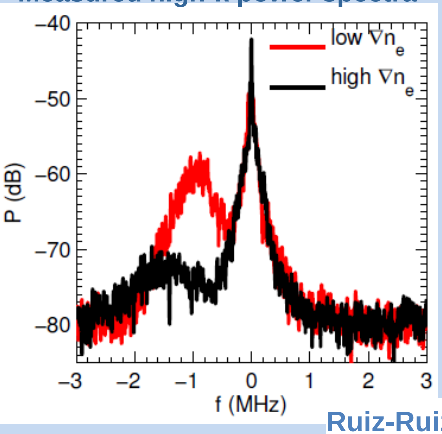
TRANSP+MMM prediction



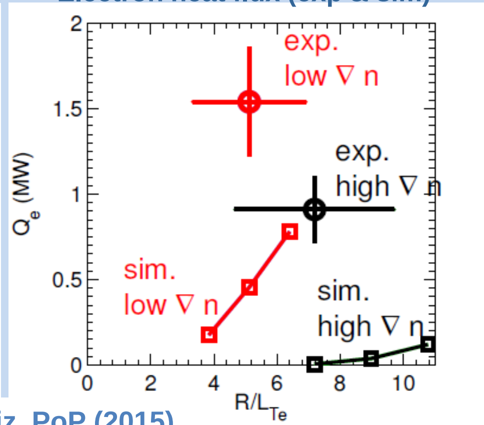
NSTX-U research will advance high-k measurement for validating ETG & multi-scale simulations

- Measured trends in high-k fluctuations (with ∇T_e, ∇n_e, s, γ_E) consistent with ETG theory (*backup*)
- BUT majority of nonlinear gyrokinetic ETG simulations predict Q_e too small to explain experiment

Measured high-k power spectra



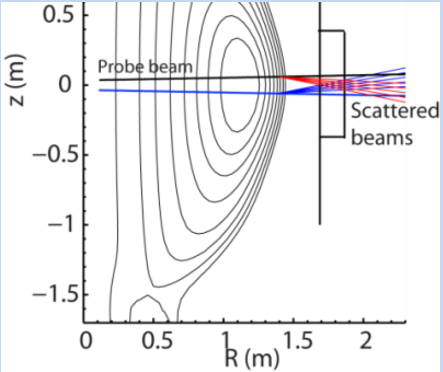
Electron heat flux (exp & sim)



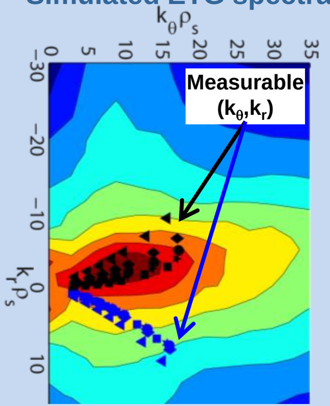
Ruiz-Ruiz, PoP (2015)

- New FIR high-k_θ scattering FDR done
  - Laser table & waveguide installed (*UC-Davis*)
- Unique dual-scattering-scheme allows for flexible measurements in 2D wavenumber space (k_θ,k_r)

New high-k scattering geometry

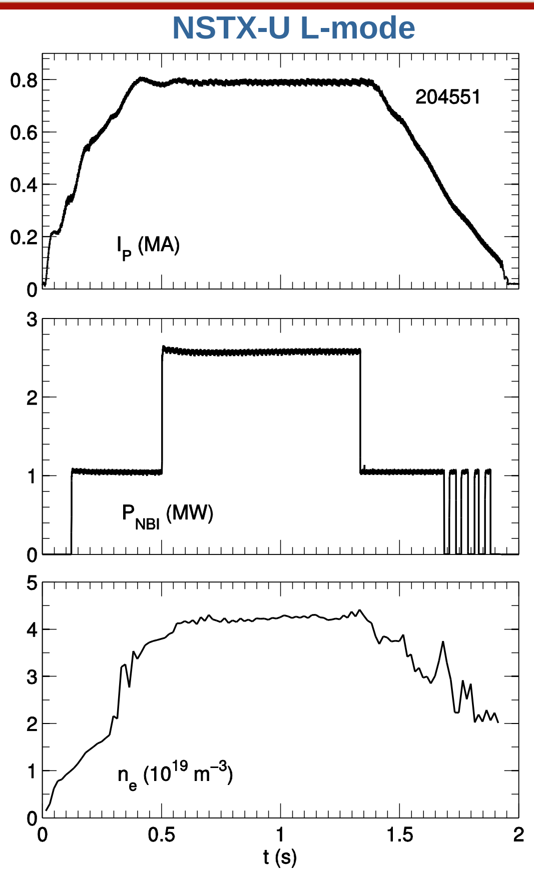


Simulated ETG spectra



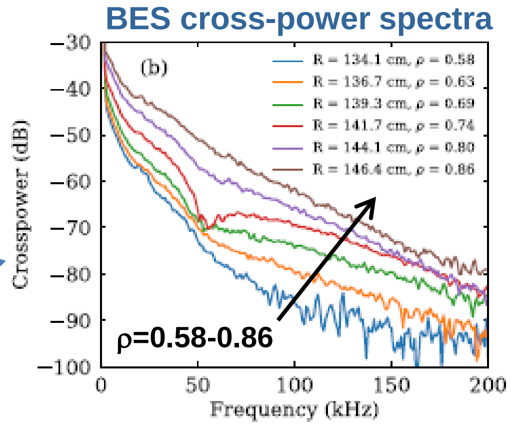
- Unique synthetic diagnostic developed to validate GK simulations (Ruiz-Ruiz, APS 2017) (*MIT collaboration*) and to enable projections for NSTX-U
- Progressing towards multiscale simulations to investigate Q_e underprediction
  - Guided by TGLF multi-scale transport model (R18-3 milestone)

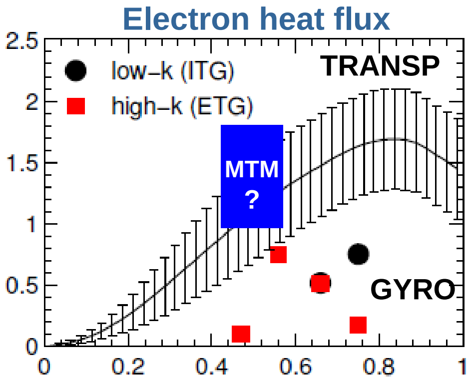
NSTX-U L-mode operation provides valuable flexibility for physics validation studies



- New centerstack allows for stationary L-mode studies
  - Was not possible in NSTX
- Ion scale turbulence data (BES) shows broadband fluctuations
- Local, single-scale GK simulations fail to capture L-mode transport
  - Complicated by multi-mode and possible multi-scale effects

⇒ **Provides low-A complement to numerous R/a=3 validation studies**





Guttenfelder (*submitted*)

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Near-term NSTX-U operational & research T&T plans focus predominantly on electron thermal transport

- Characterize H-mode confinement scaling at increased B_T, I_p, P_{NBI} → lower ν_*
  - First operation milestone (R19-1); Multiple run days scheduled for FY16

- Investigate parametric turbulence & transport dependencies and validate GK simulations and transport models
  - Exploit 2nd NBI, 3D coils and operational flexibility (*see Battaglia talk*) + comprehensive turbulence measurements

- Measure CAE/GAE activity, mode frequencies and structure
  - Exploit 2nd NBI for GAE/CAE stabilization to study impact on T_e, χ_e (*see Podesta EP talk*)

- Investigate pinch & residual stress momentum transport contributions (*follows prior ITPA work*)
  - Exploit 2nd NBI, 3D coils & long-pulse capability with new centerstack

Longer-term T&T research plans will use facility enhancements to support integrated operational goals

- Address electron particle transport in long-pulse H-modes
  - Exploit lithium and cryopump (as available) to modify sourcing (*see boundary talks*)
- Dimensionless (ν_*, β, q, ρ_*) scaling studies (requires density control)
- Measure high-Z impurity transport using LBO
  - Investigate prior to any high-Z PFC coverage (*see Jaworski talk*)
- Use RF heating (HHFW) for flexible transport studies (*see Perkins Talk*)
- Continued model validation enhancing predictive capability (*continuous process*)
  - Improved drift wave models (MMM, TGLF)
  - Develop & test $\chi_{e,EP}$ model using ORBIT + measurement/HYM predictions

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Summary: NSTX-U T&T research is addressing key issues for ST & MFE research

- Measure and understand energy confinement scaling at high field, high power to improve confidence in future ST projections (high β, low ν_*)
  - Possible due to cutting-edge facility and diagnostic capabilities
  - Will also improve integrated transport understanding to support operational goals

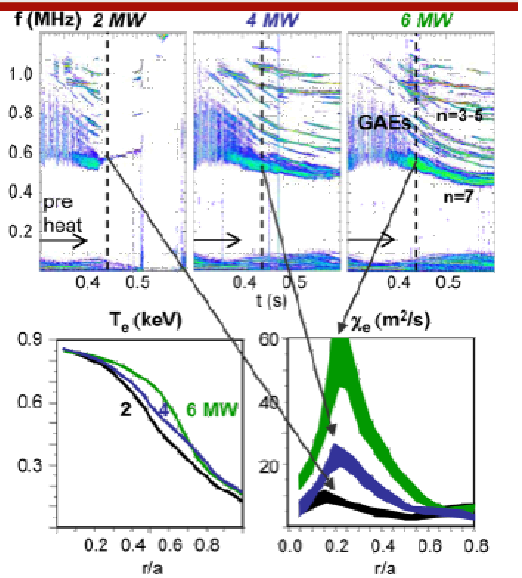
- Unique range of NSTX-U operational space (β, ν) complements tokamak and burning plasma research
  - Validating multiple drift wave and AE transport mechanisms in electron-loss dominated conditions
  - Improving theory & modeling for physics validation relevant to both ST & AT high-performance scenarios

$\Rightarrow$ Validating transport models over range of β & R/a will allow for integrated optimization (performance & engineering) of future devices

BACKUP SLIDES

Motivation: CAEs & GAEs candidates for core energy transport in NSTX

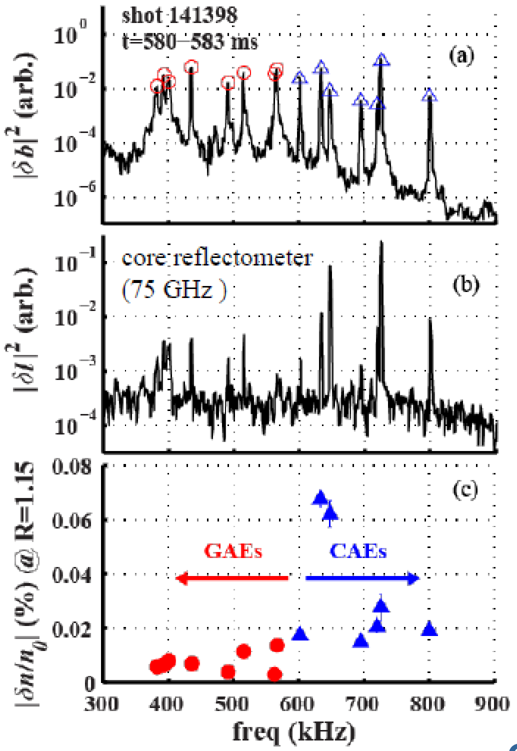
- CAEs & GAEs excited by Doppler-shifted cyclotron resonance with beam ions
  [N. N. Gorelenkov, NF 2003]
- CAE & GAE activity correlates with enhanced χ_e in core
  [D. Stutman, PRL 2009; K. Tritz, APS 2010 Invited Talk; N. A. Crocker, PPCF 2011]
  - T_e profile flattens as P_{NB} increases
  - χ_e from TRANSP modeling
- Two leading hypotheses:
  - Stochastization of e^- guiding center orbits enhance χ_e [NN Gorelenkov, NF 2010]
  - Coupling to KAWs = missing transport channel ⇒ TRANSP gets χ_e wrong [Ya.I. Kolesnichenko, PRL 2010, E.V. Belova, PRL 2015]



[D. Stutman et al., PRL 102 115002 (2009)]

Reflectometer array measures δn of CAEs & GAEs

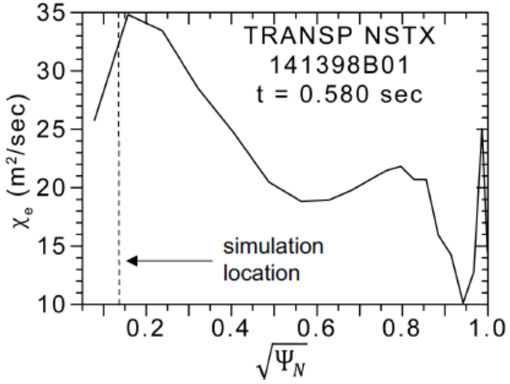
- Reflectometer array sees global modes identified as CAEs & GAEs
  [N.A. Crocker, PPCF 2011]
- New analysis gives $\delta n/n_0$; in core:
  - CAE: $\delta n/n_0 \sim 10^{-4} – 10^{-3}$
  - GAE: $\delta n/n_0 \sim 10^{-5} – 10^{-4}$
- δn from measurements via "synthetic diagnostic"
- Reflectometer "signal-to-noise" improved via correlation with δb



Crocker, NF (2013)

χ_e from GAEs simulated for 6 MW H-mode 141398, t = 0.58 sec

- Anomalous core χ_e (~ 35 m^2/s) in 6 MW H-mode
- e^- guiding center orbit spreading simulated by ORBIT => χ_e (see e.g. [NN Gorelenkov NF 2010])
  - B-field from experiment (B_{T0}=0.45 T)
  - at t = 0, isotropic thermal population (T_e = 1 keV), δ-function at $\Psi_N^{1/2}$ = 0.15
  - collisionless
  - population spreads with time => D_e, $\chi_e = \frac{3}{2} D_e$
- 8 GAEs
  - ξ_{rms} ~ 0.4 mm (using $\xi \approx (\delta n / n_0) L_n$)
  - $\omega = k_{||} V_A$ => |m| = 0 – 2
  - poloidal+toroidal Fourier modes used



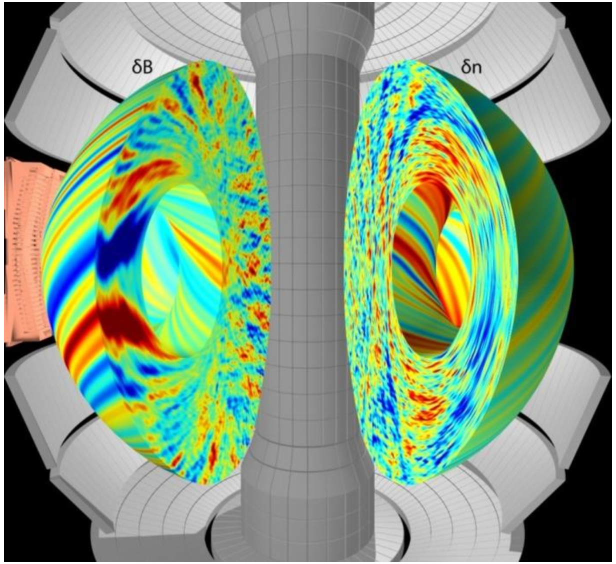
f (kHz)	n	m	ξ (mm)
383	-8	-2	0.1
393	-7	-1	0.11
401	-8	-2	0.13
436	-7	0	0.12
491	-8	0	0.06
515	-7	1	0.21
563	-6	2	0.05
567	-8	1	0.25

Crocker, NF (2017)

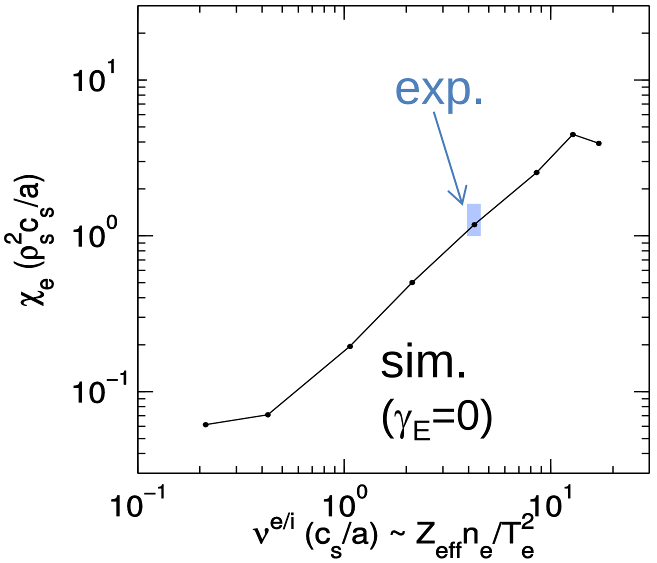
Nonlinear simulations of core MTM turbulence predict significant transport at high β & ν

- Large $\delta B/B \sim 10^{-3}$ leads to flutter transport ($\sim v_{||} \cdot \delta B^2$) consistent w/ stochastic transport
  - In the core, driven by ∇T_e with time-dependent thermal force (e.g. Hassam, 1980)
  - *Requires collisionality* $\rightarrow$ ***not explicitly driven by toroidal "bad-curvature"***
- **Collisionality scaling ($\chi_{e,MTM} \sim \nu_e$) consistent with global confinement ($\tau_E \sim 1/\nu$)**

NSTX MTM simulation



Predicted transport

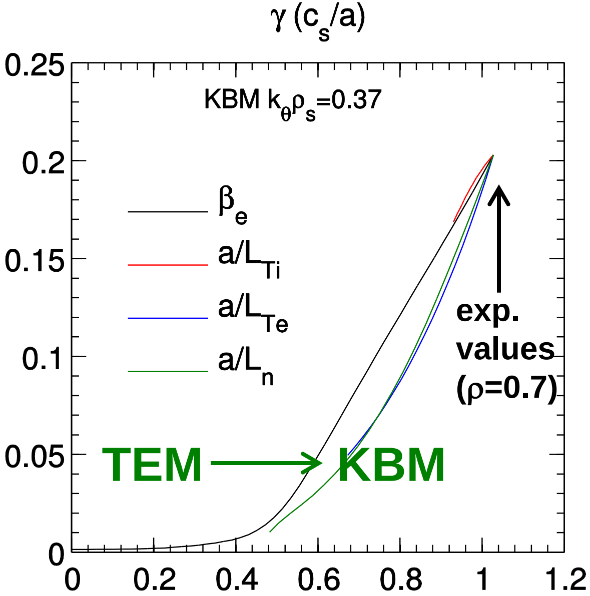


At high β & lower ν, KBM modes are predicted *in the core* ⇒ may set limit to NSTX-U confinement scaling

- KBM expected to set maximum ∇P
- Smooth transition from ITG/TEM (no hard onset) – distinct from conventional tokamaks

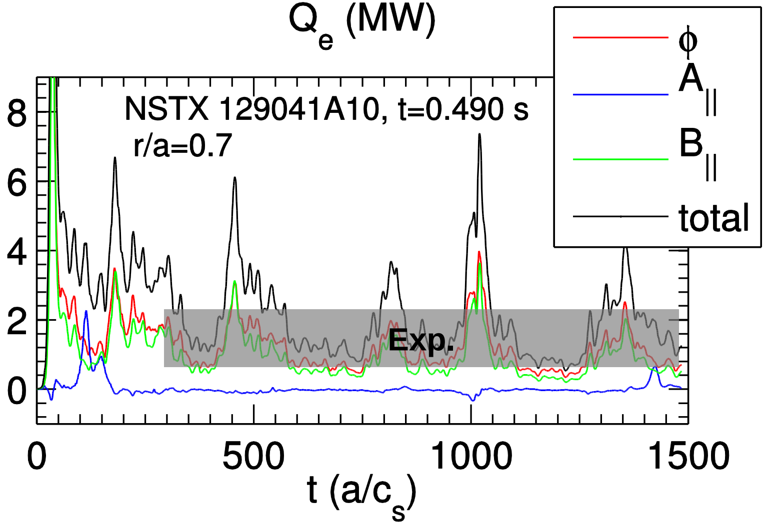
- Nonlinear simulations predict significant transport, strong compressional magnetic component ($\delta B_{||}/B \sim 10^{-3}$)

Linear growth rates



$$\alpha_{MHD} = -q^2 R \cdot 2\mu_0 \nabla P / B^2$$

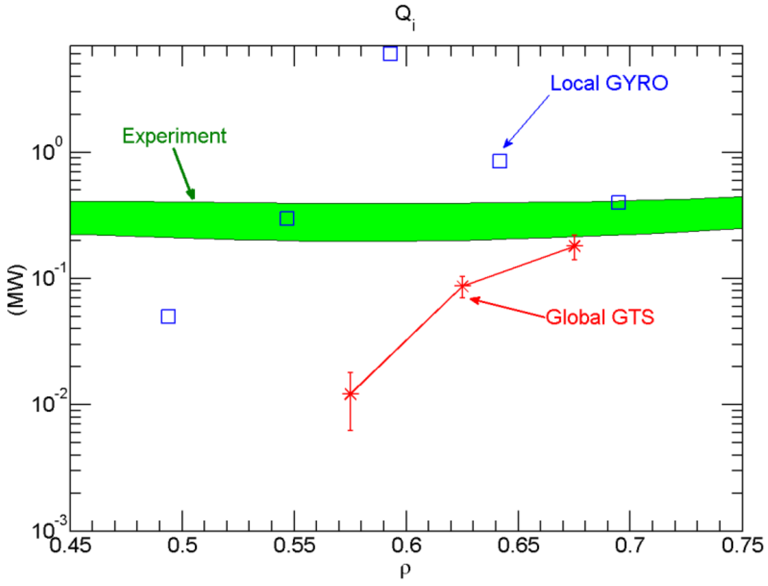
Nonlinear simulation

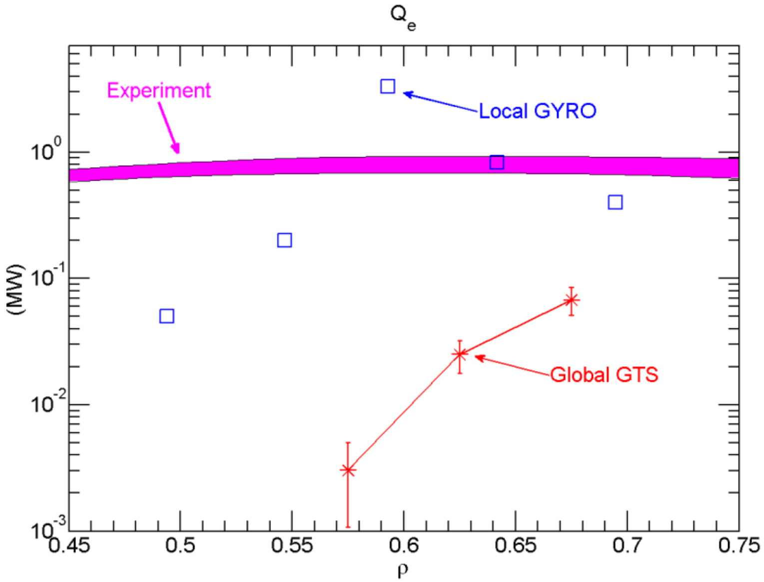


Guttenfelder, NF (2013)

Global electrostatic simulations illustrate importance of non-local effects at finite-$\rho^*=\rho_i/a$

- Significant variation in predicted L-mode heat fluxes between local (GYRO) and non-local (GTS) electrostatic simulations (Ren, NF 2013, IAEA 2016)

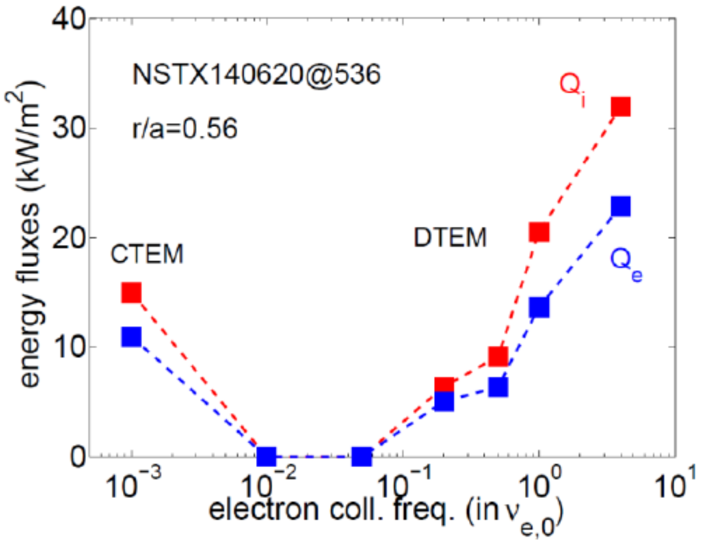




- Global effects also important for high beta → development of global electromagnetic GK codes GTS, XGC1 is advancing (*PPPL theory*)

GTS simulations: Dissipative Trapped Electron Mode (DTEM) can give favorable ν_* scaling in some regimes

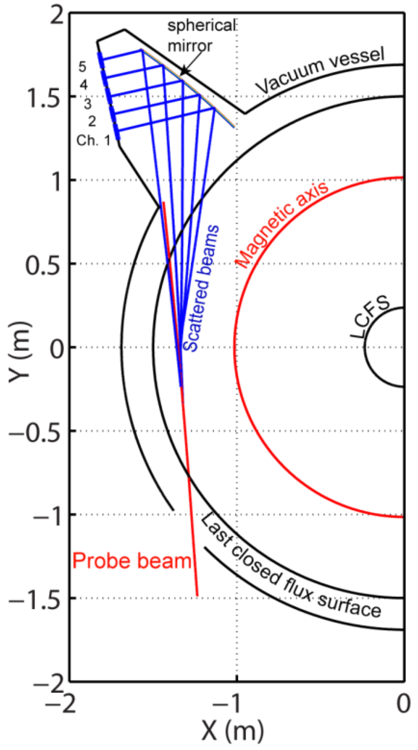
- A unique "dissipative" TEM predicted to have similar collisionality scaling to MTM for some NSTX cases.
- A Drift Wave Kelvin-Helmholtz instability, driven by parallel shear flow, is also found to be important in some NSTX cases.
  - From global **GTS** electrostatic simulation



W.X. Wang et al., NF (2015), PoP (2015)

Microwave scattering used to detect high-$k_\perp$ (~mm) fluctuations in NSTX

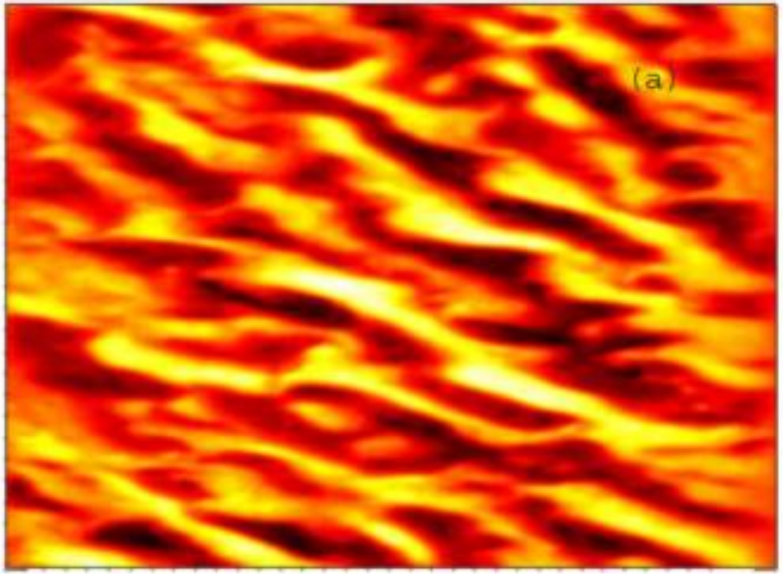
NSTX high-k scattering geometry



Mazzucato, PRL (2008)
Smith, RSI (2008)

280 GHz probe beam

ETG simulation



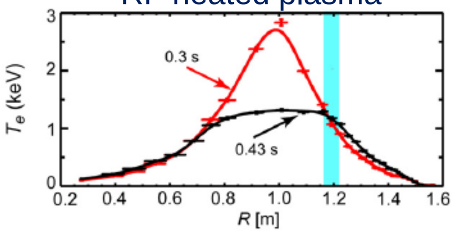
6 ion radii
360 electron radii
~2 cm

Guttenfelder, PoP (2011)

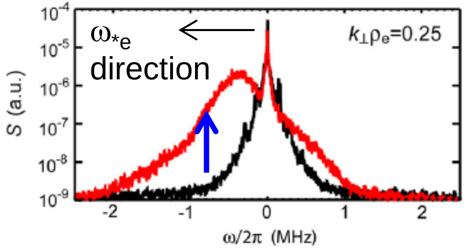
NSTX

NSTX research has extended understanding the role of high-k turbulence on electron transport

- Measured high-k fluctuations increase with ∇T_e ($R/L_{Te} > R/L_{Te,crit}$) as expected for ETG turbulence

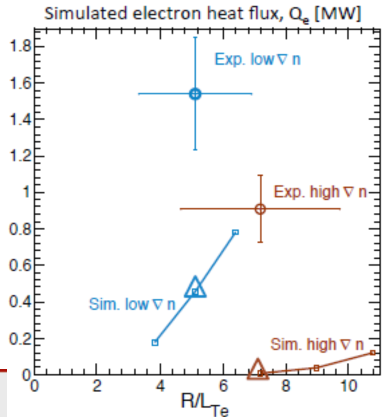


- Other measured trends are consistent with ETG theory, e.g. reduction of high-k scattering fluctuations with:
  1. Strongly reversed magnetic shear (Yuh, PRL 2011)
     - Simulations predict comparable suppression (Peterson, PoP 2012)
  2. Increasing density gradient (Ren, PRL 2011)
     - Simulations predict trend (Ren, PoP 2012, Guttenfelder NF, 2013, Ruiz-Ruiz PoP 2015)
  3. Sufficiently large E×B shear (Smith, PRL 2009)
     - Observed in ETG simulations (Roach, PPCF 2009; Guttenfelder, PoP 2011)



Mazzucato, NF (2009)

- BUT majority of nonlinear gyrokinetic ETG simulations predict Q_e too small to explain experiment



Ruiz-Ruiz, PoP (2015)

Priority NSTX-U operational & research T&T plans will focus on electron thermal transport

- Characterize H-mode confinement scaling at increased B_T, I_p, P_{NBI} → lower ν_*
  - First operation milestone (R19-1); Multiple run days scheduled for FY16
    - Q: Will $B\tau_E \sim 1/\nu_*$ remain valid (ST vs. H98 scaling)?
    - Q: Will $\chi_i \approx \chi_{i,NC}$ remain? (Hints of $\chi_i > \chi_{i,NC}$ in lowest ν_* NSTX discharges, Kaye NF 2013)

    ⇒ How favorable are projections to next-step ST devices?
- Investigate parametric turbulence & transport dependencies and validate GK simulations and transport models
  - Exploit 2nd NBI, 3D coils and operational flexibility (*see Battaglia talk*), comprehensive turbulence measurements and updated transport models (e.g. TGLF)
    - Q: Does MTM set $1/\nu_*$ scaling and/or does DTEM (Wang, PoP 2015) play a role?
    - Q: Does KBM set ultimate τ_E limit at low ν_*?
    - Q: What role does ETG play?

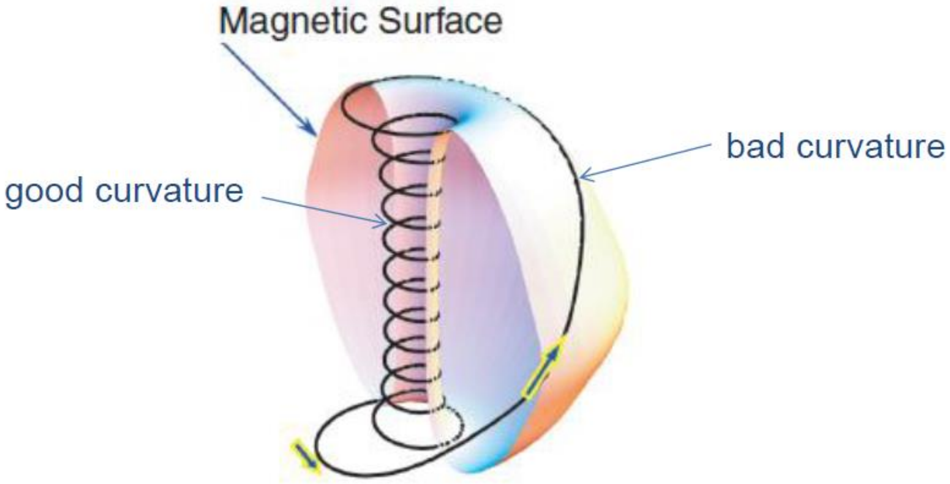
    ⇒ Can understanding be used to optimize transport characteristics?
- Measure CAE/GAE activity, mode frequencies and structure (BES, reflectometry)
  - Exploit 2nd NBI for GAE/CAE stabilization to study impact on $T_{e,0}$, χ_e (*see Podesta EP talk*)
  - Develop & test $\chi_{e,EP}$ model using ORBIT + measurement/HYM predictions
    - Q: What is role of GAE/CAE in setting $T_{e,0}$?

Long-term T&T research plans will use facility enhancements to support integrated operational goals

- Address electron particle transport in long-pulse H-modes
  - Exploit lithium and cryopump (as available) to modify sourcing (*see boundary talks*)
    - Q: How does density control/stationarity vary with transport regime? Does this influence operational goals?
- Investigate momentum transport using NBI modulation & 3D coils
  - Exploit 2nd NBI & long-pulse capability with new centerstack
    - Q: Do momentum pinch and residual stress play any significant role in setting rotation profile?
    - Follows previous work motivated by ITPA T&C (backup slides XX)
- Measure high-Z impurity transport using LBO
  - Investigate prior to any high-Z PFC coverage (*see Jaworski talk*)
    - Q: Will $D_{imp}=D_{imp,NC}$ hold? What are implications for high-Z density profile?
- Use RF heating (HHFW) for flexible transport studies
    - Q: Can impurity transport be controlled with RF?
    - Q: Can role of drift wave vs. GAE/CAE on T_e be better understood?
- Study ρ_* scaling (requires density control)
    - Q: How important are finite-ρ_* non-local effects? Can they be accurately modeled?

Many elements of ST are stabilizing to toroidal, electrostatic ITG/TEM drift waves

- Short connection length → **smaller average bad curvature**



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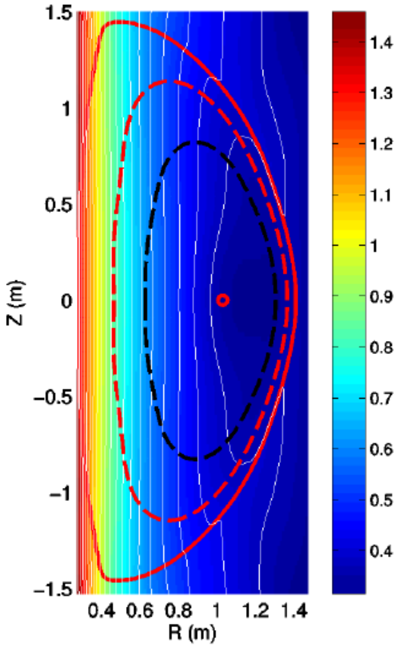

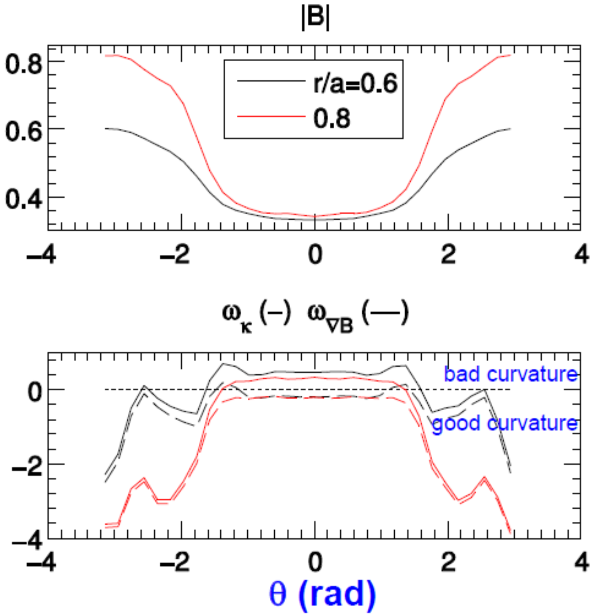

$$\vec{v}_\kappa = m v_{||}^2 \frac{\hat{b}\times\vec{\kappa}}{qB}$$

$$\vec{v}_{\nabla B} = \frac{m v_\perp^2}{2}\frac{\hat{b}\times\nabla B/B}{qB}$$

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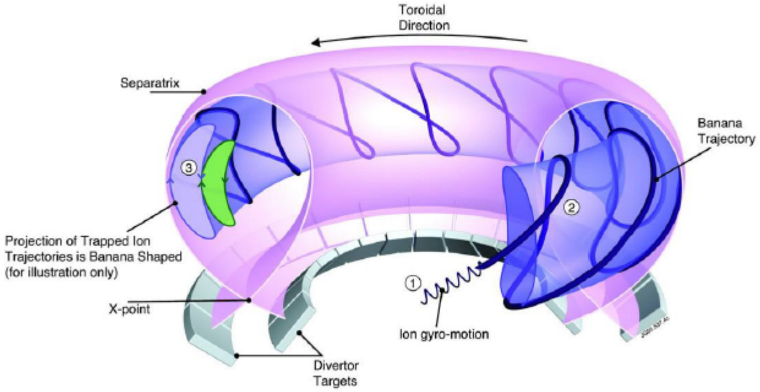

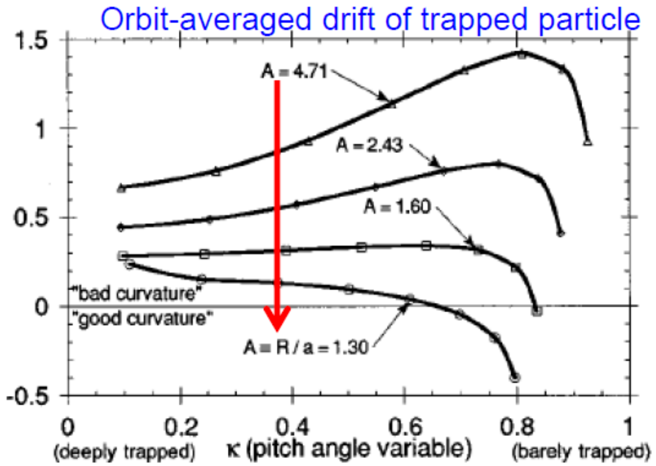

NSTX-U
34

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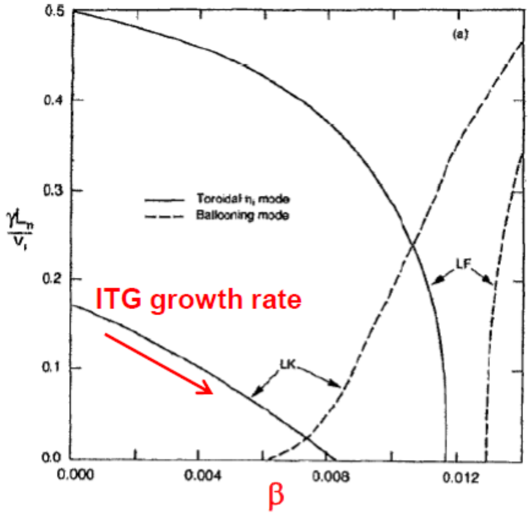

Kim, Horton, Dong, PoFB (1993)

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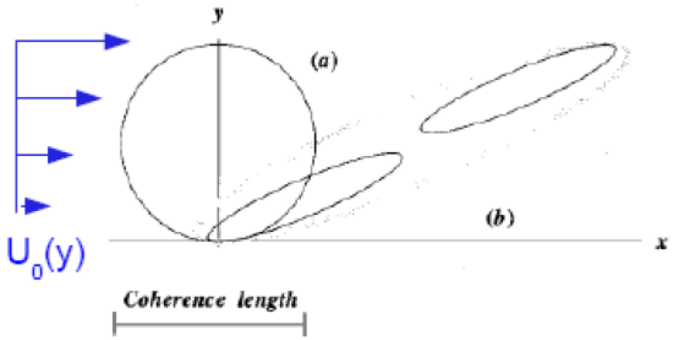

Biglari, Diamond, Terry, PoFB (1990)

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⇒**Not expecting strong ES ITG/TEM instability (much higher thresholds)**

- BUT
- High beta drives EM instabilities: microtearing modes (**MTM**) ~ $\beta_e \cdot \nabla T_e$, kinetic ballooning modes (**KBM**) ~ $\alpha_{MHD} \sim q^2 \nabla P/B^2$
- Large shear in parallel velocity can drive Kelvin-Helmholtz-like instability $\sim dv_{||}/dr$